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STUDY OF THE EQUATORIAL IONOSPHERE:

THE EQUATORIAL EVENING MINIMUM IN THE TOTAL ELECTRON CONTENT OF THE IONOSPHERE AND ITS ROLE IN EQUATORIAL SCINTILLATION

John R. Koster
Department of Physics
University of Ghana
Legon, Ghana.

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A minimum in the total electron content of the equatorial ionosphere frequently appears shortly after sunset in measurements of Faraday rotation made at Legon, Ghana (latitude 5.63°N, longitude -0.19°E, magnetic dip 8°S). This paper describes the phenomenon and investigates its occurrence characteristics over a period of six years. It concludes that the effect is due to a transport phenomenon described as a "circulation cell" which follows the sunset line. This circulation is not considered to be the primary cause of the

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CAPTIONS FOR FIGURES

ABSTRACT

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1. INTRODUCTION

Soon after synchronous satellites bearing radio beacons became available for observation at Legon, and Faraday rotation measurements began, it became obvious that something unusual was happening in the equatorial ionosphere in the period following sunset, and attention was called to this in a number of publications, (Koster, 1971; Koster, 1972; Yeboah-Amankwah and Koster, 1972; Koster, 1973). Several internal research reports gave further information about the phenomenon, (Koster, Korfker and Yeboah-Amankwah (1970), Koster and Beer (1972), Koster (1973b)). The phenomenon in question is the rapid disappearance of ionospheric ionization shortly after sunset, evidenced by a sharp drop in the value of the Faraday rotation angle. After passing through a minimum, the value of the angle often recovers again quite quickly, leading to a maximum an hour or two later before the angle decays to its diurnal minimum around the time of sunrise. Sometimes the behaviour is more irregular, and several maxima can appear. Typically, severe scintillation sets in shortly before the minimum in TEC is reached. Initially the large amplitude variations in signal strength characteristic of scintillation made accurate polarimeter readings somewhat difficult to obtain. The problem was overcome to a large extent by modifications in the Legon equipment in 1969, and good records have been obtained

since that time. Further improvements were made in the equipment early in 1972, and a large collection of reliable data is now on hand.

In previous articles we have referred to this phenomenon as the Equatorial Evening Minimum (EEM), and we shall use the same nomenclature in this paper.

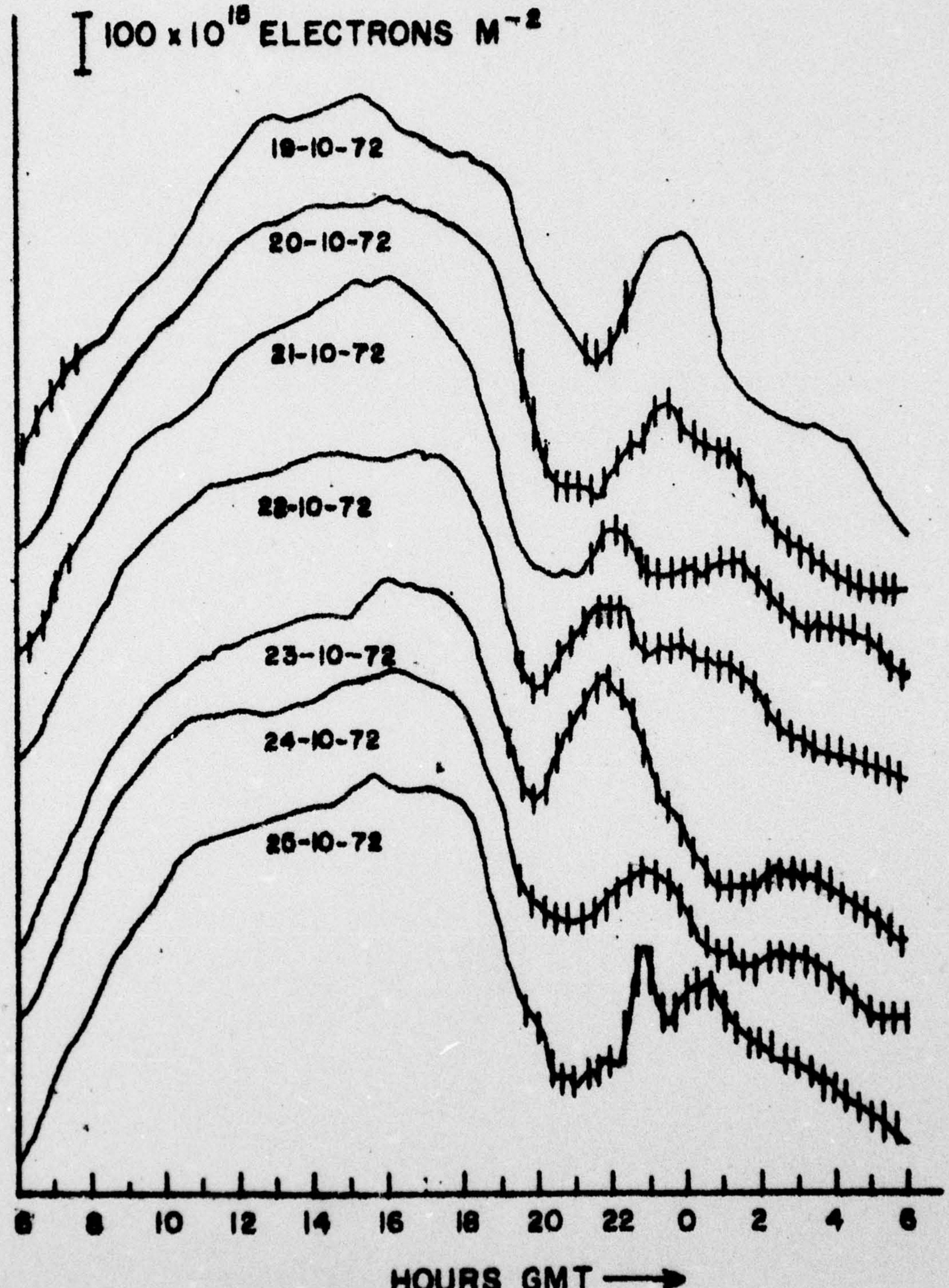
The importance of a further study of EEM is emphasized by the recent publication of two newly observed phenomena in the equatorial ionosphere.

The first of these appears in the digital power maps published by Woodman and LaHoz (1976). The remarkable "plumes" appearing in these maps gives striking evidence of regions of intense ionospheric irregularities which rise rapidly with time over the equatorial site at Jicamarca. The same maps occasionally also show patches of irregularities that have a downward movement with time.

The second discovery is the detection by "in situ" satellite observations of plasma bubbles in the equatorial ionosphere as described by McClure, Hanson and Hoffman (1977). It seems highly likely that EEM is but another aspect of this observed "bubble" phenomenon, and a study of EEM can throw further light on the mechanism behind all these new manifestations of irregularity production and movement over the equator.

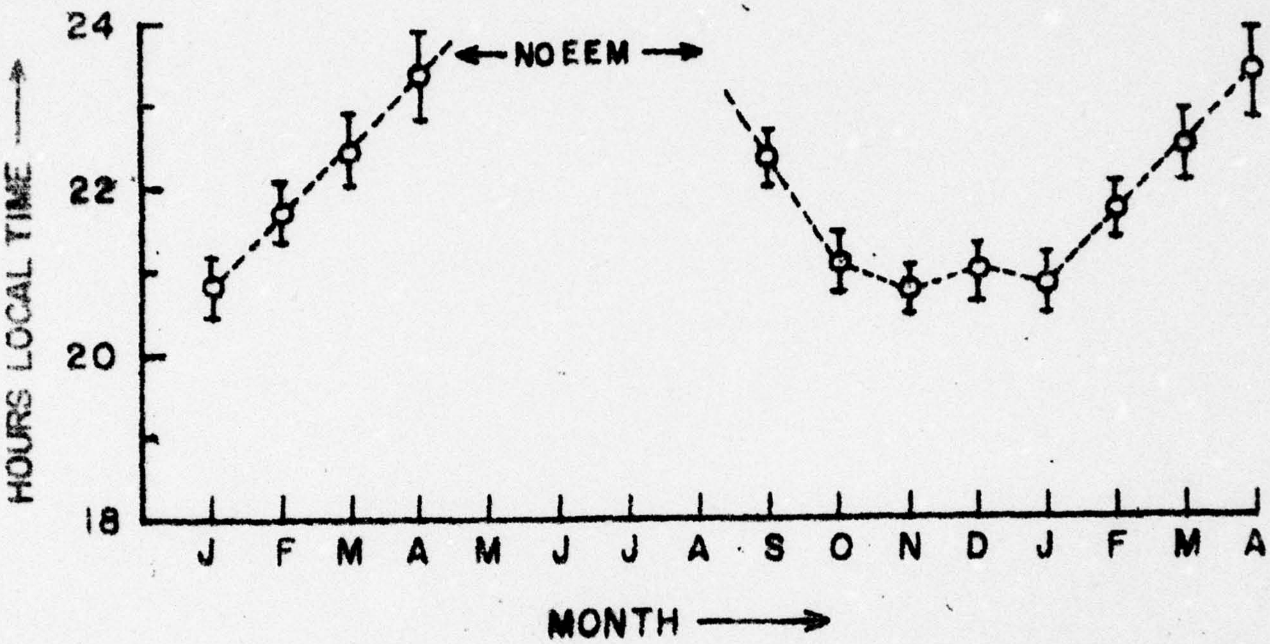
2. A BRIEF DESCRIPTION OF THE PHENOMENON

Quite a number of plots of total electron content (TEC) versus time have appeared in the literature. We here reproduce only one figure to illustrate the general characteristics of the equatorial evening minimum. Figure 1 shows a plot of TEC as a function of time as observed at Legon on seven consecutive days in October, 1972. Electron content is normally at its daily minimum at sunrise, so the plots commence at 6 a.m. local time on the days in question and continue till 6 a.m. on the following day. The vertical scale of the plots, in terms of TEC per unit distance, is shown on the figure. The outstanding feature in the curves is the sharp decline in TEC after ionospheric sunset, leading to a minimum around 21 hours local time. The considerable variability of this feature from day to day is well illustrated in the figure. The periods during which severe amplitude variations (scintillations) occurred are indicated by short vertical lines across the curve.


100 x 10^15 ELECTRONS M^-2
19-10-72
20-10-72
21-10-72
22-10-72
23-10-72
24-10-72
25-10-72
6 8 10 12 14 16 18 20 22 0 2 4 6
HOURS GMT

3. EEM AND TIME OF DAY

The actual time of occurrence of the equatorial evening minimum was initially treated in an internal scientific report (Koster, 1973b). This treatment is here brought up to date, making use of data up to April, 1977 - six effective years of observation. The equatorial evening minimum is, as has been mentioned before, a fairly regular phenomenon, in that it shows up in the monthly mean plots of TEC against time in all months except those around the June solstice. Figure 2 was produced by finding the time of occurrence of the evening minimum in the monthly mean curve for each of the 68 months investigated. These were grouped, by month, as shown in the figure. The error bars indicate one standard deviation in either side of the plotted point. We note that the minimum occurs around 21 hours in January. It appears progressive later until the effect disappears in May. It reappears in September, becoming progressively earlier till it again occurs around 21 hours for the months of October through January.


24
22
20
18
HOURS LOCAL TIME
NO EEM
J F M A M J J A S O N D J F M A
MONTH

4. DETERMINING A MEASURE OF EEM

Before we can discuss EEM in quantitative terms, we must define some (preferably simple) way of measuring it. A number of different definitions have been used over the years - each with its advantages and limitations. For the purposes of this paper, we shall adopt a measure that is simple in itself, and easy to implement.

We have on hand TEC values, taken at 10 minute intervals on a continuous basis. EEM for a given day is defined in terms of the maximum slope of this TEC versus time curve between the hours of sunset and midnight. Our actual definition is the following:

$$\text{EEM} = \frac{\text{MAXIMUM SLOPE OF THE TEC VERSUS TIME CURVE BETWEEN 18H AND 24H}}{\text{VALUE OF TEC AT 18H}}$$

On days on which TEC decreases continuously, EEM will be negative. Days of progressively larger rises in TEC in the time interval under consideration will have progressively larger and positive values of EEM.

Division by the TEC value at 18 H is done to make our measure of EEM a relative one, rather than an absolute one. Any definition that uses absolute values of TEC will almost certainly produce equinoctial maxima in the annual curve of EEM, since TEC

is known to have maxima at those times (Koster, 1972). Such a definition would also produce a maximum in the sunspot cycle variation of EEM, since TEC is also known to be at its greatest near sunspot maximum. We are interested in knowing whether the relative effectiveness of the mechanism producing EEM has a seasonal and a solar cycle dependence.

5. THE ANNUAL BEHAVIOUR OF EEM

To investigate the variation of EEM with season, the year was divided into 13 28-day periods. Just over 8 years of data entered the analysis. The mean value for each of the 13 annual periods was taken. If we express our tabulated function as a Fourier series in the form:

$$F(x) = A_o + \sum_{k=1}^{6} A_k \cos kx + \sum_{k=1}^{6} B_k \sin kx$$

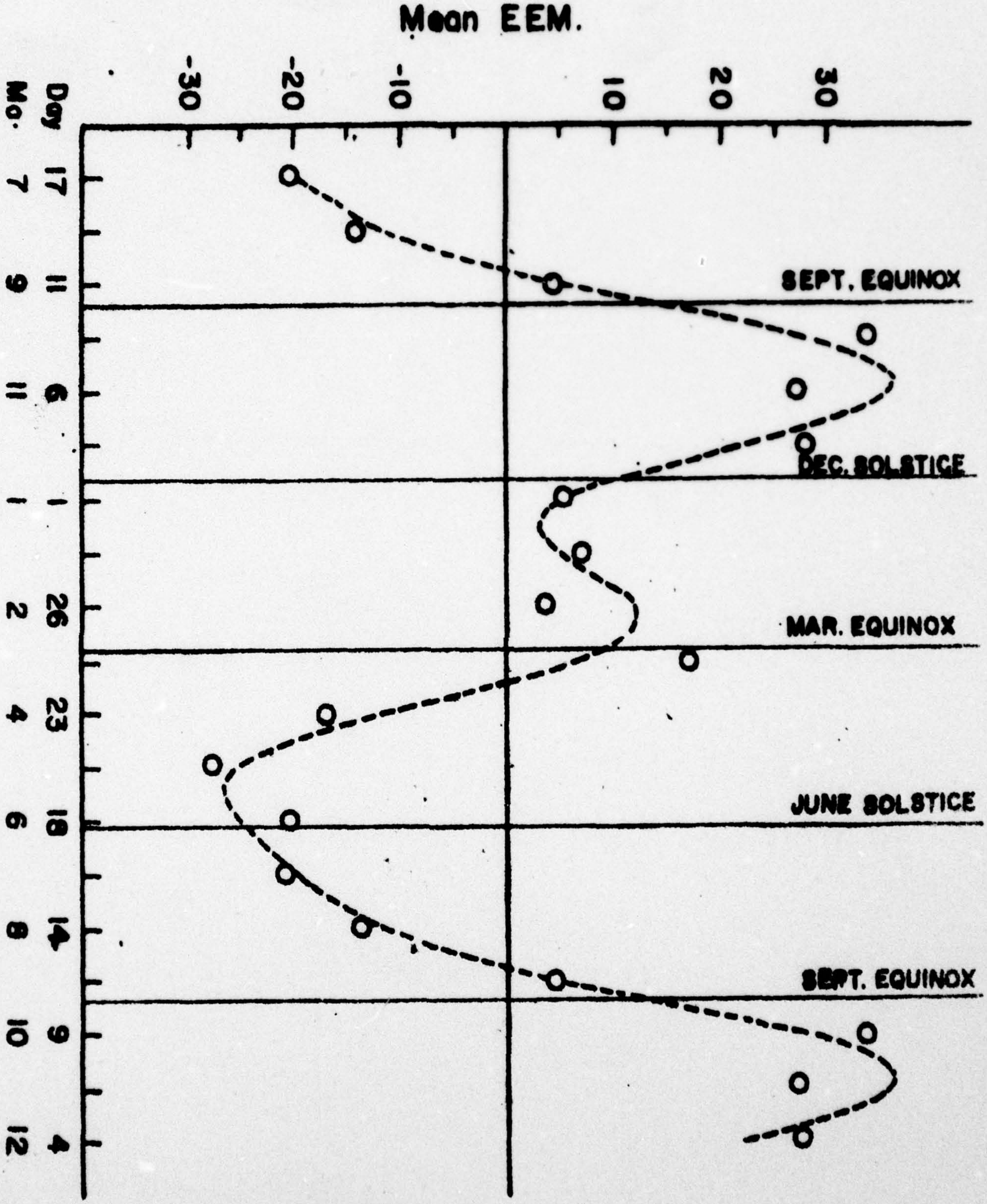
the coefficients A and B can readily be calculated. Their values are given in the table below.

k	0	1	2	3	4	5	6
A_k	1.98	-17.38	-10.20	6.07	0.91	-1.24	-0.74
B_k	0.00	15.99	2.71	-2.92	-5.11	-0.23	5.52

TABLE 1. Fourier components of the annual variation of EEM.

The curve described by the constant and the first three harmonic terms is sketched into Figure 3.

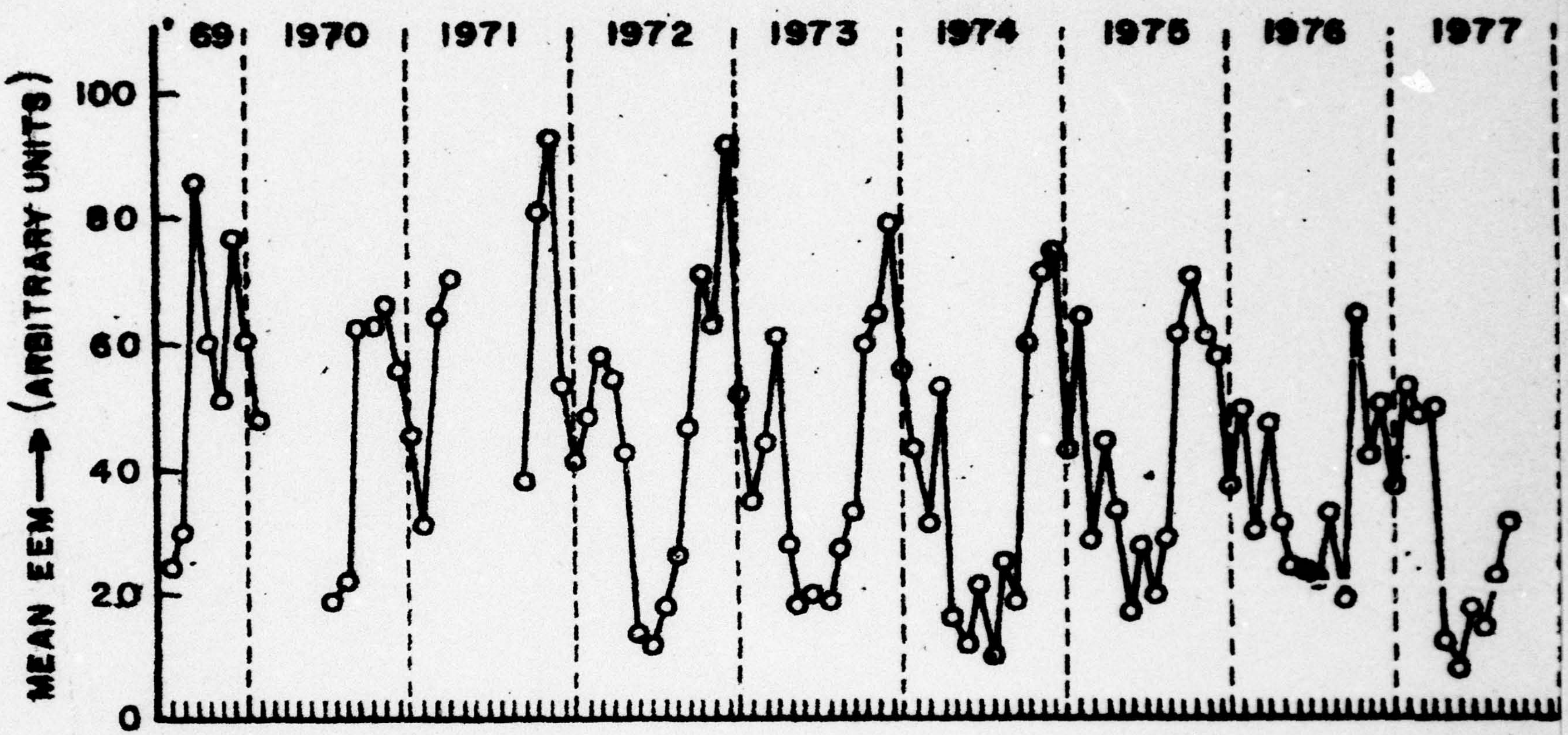
We note that the annual term predominates. The second harmonic is down by a factor of 0.64, and the other harmonics have values less than this. The maximum occurs in October, and the broad minimum in May, June and July.

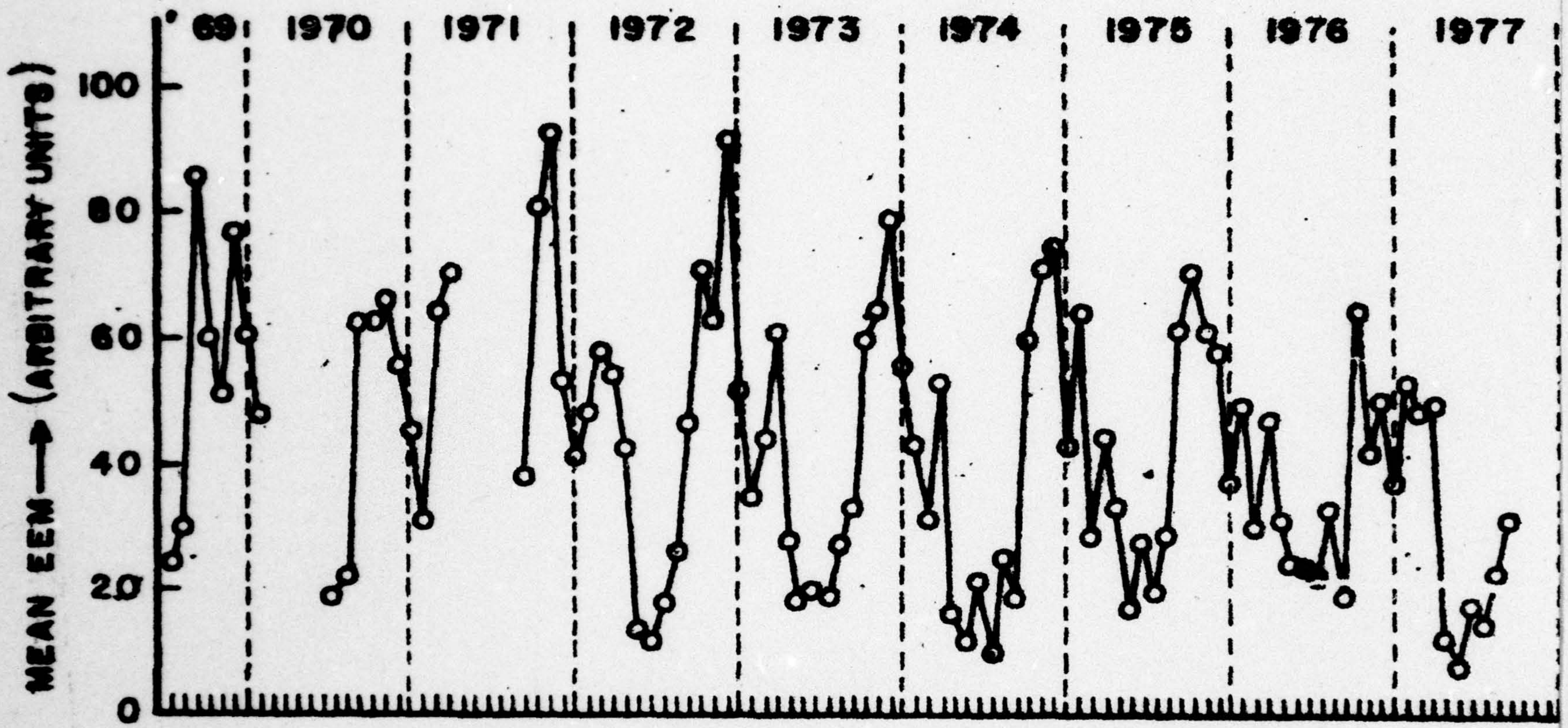

Mean EEM.
-30
-20
-10
10
20
30
Day
Mo.
17
7
11
9
6
11
1
1
26
2
23
4
18
6
14
8
9
10
4
12
SEPT. EQUINOX
DEC. SOLSTICE
MAR. EQUINOX
JUNE SOLSTICE
SEPT. EQUINOX

6. THE VARIATION OF EEM WITH SUNSPOT CYCLE

Figure 4 is a plot of the mean value of EEM for each 4 week period (13 points annually) from July 1969 until August 1977 inclusive.

We note that the same general shape repeats itself annually with essentially the same amplitude over the eight years covered. Since this extends from sunspot maximum to sunspot minimum, we conclude that there is no appreciable sunspot cycle variation in the phenomenon. We must mention again, however, that it is the relative change in TEC that remains nearly constant. Absolute values would differ by a factor of two or three.


MEAN EEM ⟶ (ARBITRARY UNITS)
0
20
40
60
80
100
'69
1970
1971
1972
1973
1974
1975
1976
1977


'69
1970
1971
1972
1973
1974
1975
1976
1977
MEAN EEM ⟶ (ARBITRARY UNITS)
100
80
60
40
20
0

7. THE VARIATION OF EEM DURING MAGNETIC STORMS

To determine this variation, continuous periods of 200 days were taken, extending from 16 September to 3 April, on each of six consecutive years. This procedure was resorted to in order to avoid including the time of year during which the value of EEM is exceedingly small. Values of EEM for each of the 200 days were correlated with the corresponding sums of the daily K_p values. The correlation coefficients turned out to be:

YEAR	CORRELATION COEFFICIENT (CC)
1971/72	+ 0.001
1972/73	- 0.098
1973/74	- 0.083
1974/75	- 0.060
1975/76	- 0.120
1976/77	+ 0.108
MEAN CC	- 0.042 ± 0.084

We conclude that there is no significant correlation between the two parameters.

8. SCINTILLATION AND THE EQUATORIAL EVENING MINIMUM

Figure 1 depicts the usual relationship between the occurrence of the equatorial evening minimum and severe equatorial scintillation. On most of the days depicted, severe scintillation commenced near the bottom of the initial fall in the value of the TEC, and continued for a number of hours thereafter - often throughout the night. On the very first day, however, (19 October, 1972) a rather large magnetic storm ($\Sigma K_p = 33$) occurred. On that day, although the value of EEM was relatively large (59.8), the value of TEC at the time of the evening minimum remained high (above 300×10^{15} electrons m^{-2}). When this occurs, scintillation at Legon is normally absent or greatly reduced (Koster, 1972). As Figure 1 shows, scintillation occurred for only an hour during this night, and the value of the scintillation index remained modest. On all the other days, the scintillation was severe, both as regards intensity (as evidenced by the scintillation index) and duration.

Here we wish to note two things:

(a) The onset of scintillation normally coincides in time with the occurrence of EEM on days on which EEM is present.

(b) Scintillation is normally severe when EEM is large unless the TEC value remains abnormally high, as it does frequently during severe magnetic disturbances.

To obtain a more quantitative measure of the relationship between EEM and scintillation the nightly value of EEM, as defined earlier, was correlated with the sum of the scintillation indices (SI) for the same night. Data were taken on a yearly basis. The correlation coefficients obtained are tabulated below.

YEAR NO.	MONTHS INCLUDED	CORRELATION COEFFICIENT
1.	9-71 to 8-72	0.314
2.	9-72 to 8-73	0.293
3.	9-73 to 8-74	0.247
4.	9-74 to 8-75	0.299
5.	9-75 to 6-76	0.420
6.	7-76 to 4-77	0.208

TABLE 2. Yearly correlation coefficients between EEM and the sum of the nightly scintillation indices.

The above results are significant on the 0.1% level, so we must conclude that there is some connection between scintillation and the equatorial evening minimum. In determining the above correlations each of the 6 years was divided into 13 28-day periods, and the correlation coefficient was calculated for each period as well as for the entire year. The 13 values for a given year fluctuated wildly, and their mean value

was statistically insignificant. We conclude that the significant correlation between KEM and SI on an annual basis is due largely to the similar seasonal variation of the two phenomena, and not to a close day to day correspondence over a period as short as a month.

9. TEC AND SATELLITE ELEVATION

The results reported above were made from the analysis of records obtained from the observation of the satellite ATS-3 during the 6 year period in which it was kept on station at 70° west longitude. The elevation angle from Legon was 12°. Observations at higher elevation angles were also desired, and observations were made on IS2F3 from March 1973 through April 1974, during which time the satellite was at an elevation of approximately 65°. A number of difficulties accompanied this venture.

(a) At Legon, as a synchronous satellite moves to high elevations, the M values become progressively smaller. Should the satellite also have an inclined orbit (IS2F3 had an inclination of between 4° and 5° at this time) the value of M becomes even smaller when the satellite moves to negative latitudes. Eventually the value of M becomes so small that the quasi-longitudinal (QL) approximation on which most of the Faraday rotation reductions depend becomes inapplicable. Because of this problem, only the March and April records of 1973/74 had sufficiently large values of M throughout the night to make their use reliable.

(b) For a period of around 6 weeks near the equinoxes, a synchronous satellite is eclipsed each night at an hour that

depends on its longitude. This eclipse is of just over an hour's duration at its maximum. During an eclipse, there is likely to be a considerable temperature change in the satellite, with corresponding frequency drifts on the part of its oscillator. A loss of power from its solar cells normally leads to a drop in signal intensity as well unless on-board batteries are able to provide energy during the eclipse time. Hence, care must be taken in utilizing results obtained around the equinoxes from a synchronous satellite.

In spite of the above, records of good quality were obtained during March and April of both years. Values of EEM for these periods are summarized in the table below.

ELEVATION	65^{o}	12^{o}
SATELLITE	IS2F3	ATS-3
PERIOD	MEAN EEM	
Mar/Apr '73	38.5 ± 3.0	16.3 ± 2.5
Mar '74	33.6 ± 3.8	13.1 ± 2.1
Apr '74	13.1 ± 1.7	5.7 ± 2.3

TABLE 2. Mean values of EEM for simultaneous observations of two satellites at different elevation angles.

We conclude from the above that one observes larger values of EEM when looking at a high elevation satellite than when simultaneously observing a low elevation one. We would further like to remark that the correlation between the pairs of day to day values of EEM is relatively low. The significance of these observations will be commented on below.

When one draws pairs of curves for a given day on a common coordinate system, there is such a diversity of small features on the two curves that detailed comparison is difficult. However, a few general conclusions can be drawn.

(a) The TEC curve derived from the Faraday rotation of the signal from the high elevation satellite shows more and larger features of shorter duration than does the curve from the low elevation counterpart. This merely verifies what Table 2 above shows in a more quantitative form.

(b) A minimum in TEC normally occurs sooner on the curve from the easterly satellite than it does on that from the westerly one. This was true for 58 of the 76 daily records examined. This suggests a westward velocity. Only occasionally is there a feature that suggests a possible eastward velocity.

(c) The monthly mean curves for the months of March '73 and March '74 both show a definite though small evening minimum for both satellites. In each case the minimum

in the curve from the easterly satellite precedes in time that for the westerly one. The actual separation of the ionospheric points (i.e., the points where the two lines of sight penetrate the 420 km level in the ionosphere) is 1200 km. The mean time lag between the minima is 40 minutes, corresponding to a velocity of 500 ms^{-1}. We recall that the velocity of the sunset line at this height at the equator is 495 ms^{-1}. We conclude that the time of the minimum on a TEC curve is closely associated with the local time at the ionospheric point.

10. SUMMARY OF FINDINGS

We here summarize the findings thus far made concerning the behaviour of the EEM:

(a) EEM has a seasonally variable occurrence time, appearing around 21 hours from October through January. It occurs progressively later from February through April, and disappears entirely from the monthly means from May through August. It reappears at 23 hours in September, and moves forward to 21 hours again in October.

(b) The amplitude of EEM has a predominant annual component, with a second harmonic down by a factor of 0.64. There is a broad minimum around the June solstice, and a maximum in October.

(c) The relative measure of EEM adopted in this paper shows little dependence on the sunspot cycle.

(d) The amplitude of EEM is uncorrelated with magnetic disturbances.

(e) EEM is greater for high elevation satellites than for low ones.

(f) EEM occurrence times generally follow the sunset line - appearing first on an easterly satellite, later on a westerly one. The time difference corresponds to the velocity of the sunset line (ca 495 ms^{-1} at 420 km).

11. DISCUSSION OF FINDINGS

Our purpose in this paper is to investigate the behaviour of the equatorial evening minimum with a view to understanding the physical mechanism which gives rise to it. We specifically wish to see whether we can throw any new light on the mechanism giving rise to equatorial scintillation. With this in view, we consider each of the above findings.

(a) Does the onset time of EEM bear any relationship to scintillation? Scintillation has an onset time that varies by about an hour during the course of the year. The monthly mean onset time in October occurs about an hour earlier than at the June solstice. A considerable fraction of the onset time change in scintillation disappears if we use apparent (i.e. sundial) time instead of mean time. The small remaining change in scintillation onset time is in phase with the onset time changes of EEM, but very different from it. It will be remembered that EEM disappears completely at the June solstice. We conclude that EEM cannot be a primary cause of scintillation, since the latter occurs at all months, even those in which no EEM is visible. The most that our evidence can suggest is that EEM may in some way be associated with an enhancement of scintillation. At Legon the average nightly duration of scintillation as obtained from the monthly means is some 7 hours at the

June solstice, around 10 hours in October through December. It is quite possible that EEM is associated with the rise of "bubbles" through the ionosphere, giving rise to very intense scintillation which persists for a longer time, while scintillation occurring in the absence of EEM is due to irregularities confined to the bottom of the F region. These scintillations might well be of lesser intensity and shorter duration.

(b) The annual component in the amplitude of EEM agrees quite well with the annual variation of scintillation. This observation is consistent with the hypothesis that scintillation accompanied by EEM is more severe than that which occurs during its absence.

(c) The lack of dependence of EEM on sunspot cycle variations does not contradict our hypothesis. If one uses a definition of EEM that measures the absolute change in electron content rather than its relative change, EEM would show a sunspot cycle variation similar to that exhibited by scintillation. The independence of the relative measure of EEM from sunspot cycle variations suggests that EEM depends on some physical parameter of the sun which changes annually relative to the earth, but which does not depend directly in the solar EUV flux, sunspot number or any other parameter which would surely show an 11 year variation. We suggested before (Koster, 1973) and wish to suggest again, that this parameter is the direction of the

solar rays relative to the magnetic field lines at Legon.

(d) We next consider the lack of significant correlation of EEM with K_p. During severe magnetic storms, scintillation at Legon is often suppressed. At such times we often have large values of EEM (see curve 1 in Figure 1). Hence, there is surely no one-to-one relationship between scintillation and EEM. What it does suggest is that, when the conditions for scintillation (whatever they are) are right, the scintillation will be more severe and lasting when a large EEM is present than when it is absent. When the conditions are not right, there may be no scintillation in spite of the presence of large EEM.

(e) The enhancement of EEM for high elevation satellites is interpreted as meaning that the region of electron depletion (the "bubble") is often of limited extent relative to the total path length of the wave through the ionosphere. If we take a simple case where the vertical E-W section of a single "bubble" is circular, the relative depletion along the path to an overhead satellite would be much larger than that to a low elevation satellite, whose total path through the ionosphere may be several times longer. Hence, the higher satellite would display a larger EEM - as is the observed fact.

(f) On the majority of occasions when simultaneous Faraday rotation results have been available from two satellites, the

KEM has appeared first on the satellite that is further east, later on the one that is to the west of it. The time differences agree remarkably well with the velocity of the sunset line (495 ms^{-1} at the equator). This suggests a basic dependence of KEM on the apparent time at the subionospheric point. KEM seems to be triggered by ionospheric sunset, with a time lag that is a function of season.

12. CONCLUSIONS

The evidence found in this investigation seems to be entirely consistent with the picture of a "circulation cell" previously suggested (Koster, 1973), and we shall repeat its essential features here.

A large "circulation cell" moves westward along the equator at the speed of the sunset line. We are thinking here in terms of circulating magnetic field lines which have ionization "frozen" on them. A vertical E-W section of this cell would show an upward velocity on its leading edge, an eastward velocity at the top, a downward velocity on the trailing edge, and a westward velocity at the bottom. These upward and downward velocities are consistent with the measurements of Balsley and Woodman (1971). As the leading edge of the cell passes over an observer at the equator, he observes not only a large upward velocity of the F region ionization above him, but also a sharp drop in the Faraday angle he is measuring, since the electrons are moving upward and eastward, out of his line of sight. The field lines moving in from below are largely devoid of electrons, since they move in from the E region or lower, where the electron content has fallen drastically due to recombination.

When the trailing edge of the cell passes over the observer sometime later, he measures a large downward velocity of ionization, and his Faraday angle increases sharply due to the movement of electrons into his line of sight from above and from the west.

This circulation can only begin after sunset at the ends of the field lines to which the F region ionization is frozen. The magnetic field lines at Legon have a westward declination of 9°, while those at the subionospheric point of ATS-3 have a declination of 14°. If one adds to this the fact that the dip equator at the longitude of Legon (0°) is some 10° North of the geographic equator, it becomes obvious that the controlling factor will normally be sunset at the northern end of the field lines in question. Circulation should, therefore, be delayed at Legon around the June solstice, when sunset there is very late. This agrees extremely well with the observations reported above.

Our observations force us to conclude that the circulation cell is not the primary cause of the formation of irregularities, and hence of scintillation. We have evidence of a large EEM, and hence a vigorous circulation during magnetic disturbances, when there is no scintillation. And during the June solstice we have quite frequent scintillation, but no evidence of circulation.

But the circulation, of which the EEM is a measure, can easily enhance scintillation in two ways. The circulation cell can lift irregularities, initially formed near the bottom of the F region, into regions where they will persist much longer. It can, in fact, fill the whole region with irregularities, thus enhancing the intensity of the observed scintillation. And the circulation cell can cause scintillation to persist for a much longer time, by lifting irregularities to great heights, where recombination times are much longer. The 7 hour duration of scintillation during the June solstice, compared to the 10 hour duration in October, could best be explained in this way.

Our picture would suggest that the seasonal behaviour of scintillation at Legon may depend to a large extent on the peculiar orientation of the earth's magnetic field lines at this longitude. Other longitudes might well observe a very different seasonal behaviour.

We conclude that the EEM, though not a primary cause of the production of irregularities in the equatorial ionosphere, is an important contributing factor in increasing the intensity of equatorial scintillation by lifting already formed irregularities to great heights, and in increasing its duration by enabling these same irregularities to persist for a longer time.

It seems quite obvious that the EEM is but another manifestation of the rise of plasma bubbles through the ionosphere as measured in situ by the explorer satellites (McClure et al, 1977), and appearing as dramatic plumes in the VHF radar range-time-intensity maps produced by the Jicamarca group (Woodman and La Hoz, 1976).

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